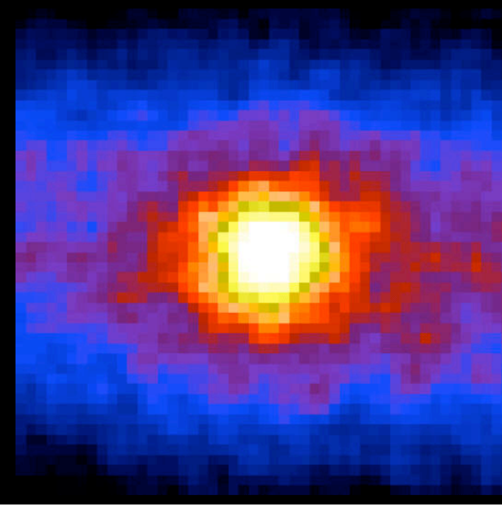
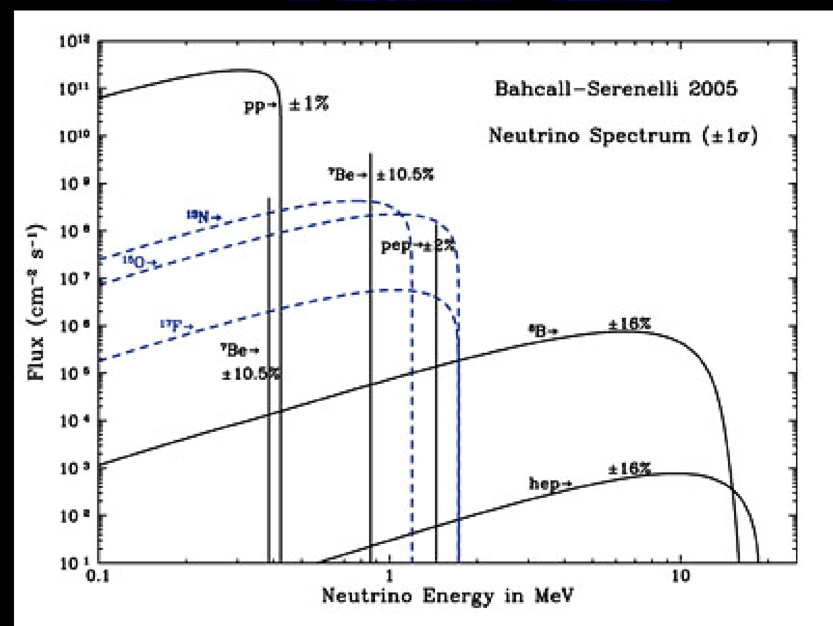
Nuclear Astrophysics at DUSEL

Paul Vetter, Daniela Leitner, Matthaeus Leitner,
Alberto Lemut

What do solar neutrinos tell us?

- Solar energy production
- Solar properties at core
  - Temperature
  - metallicity
- Neutrino properties?
  - Mixing angle
  - Mass difference
  - Matter enhanced oscillations





Solar pp chain ($4p \rightarrow \alpha + 2e^+ + 2\nu_e$)

$p + p \rightarrow {}^2H + e^+ + \nu_e$ (99.75%)

$p + e^- + p \rightarrow {}^2H + \nu_e$ (0.25%)

${}^2H + p \rightarrow {}^3He + \gamma$

85%: ${}^3He + {}^3He \rightarrow {}^4He + 2p$

15%: ${}^3He + {}^4He \rightarrow {}^7Be + \gamma$

10^{-5} %: ${}^3He + p \rightarrow {}^4He + e^+ + \nu_e$

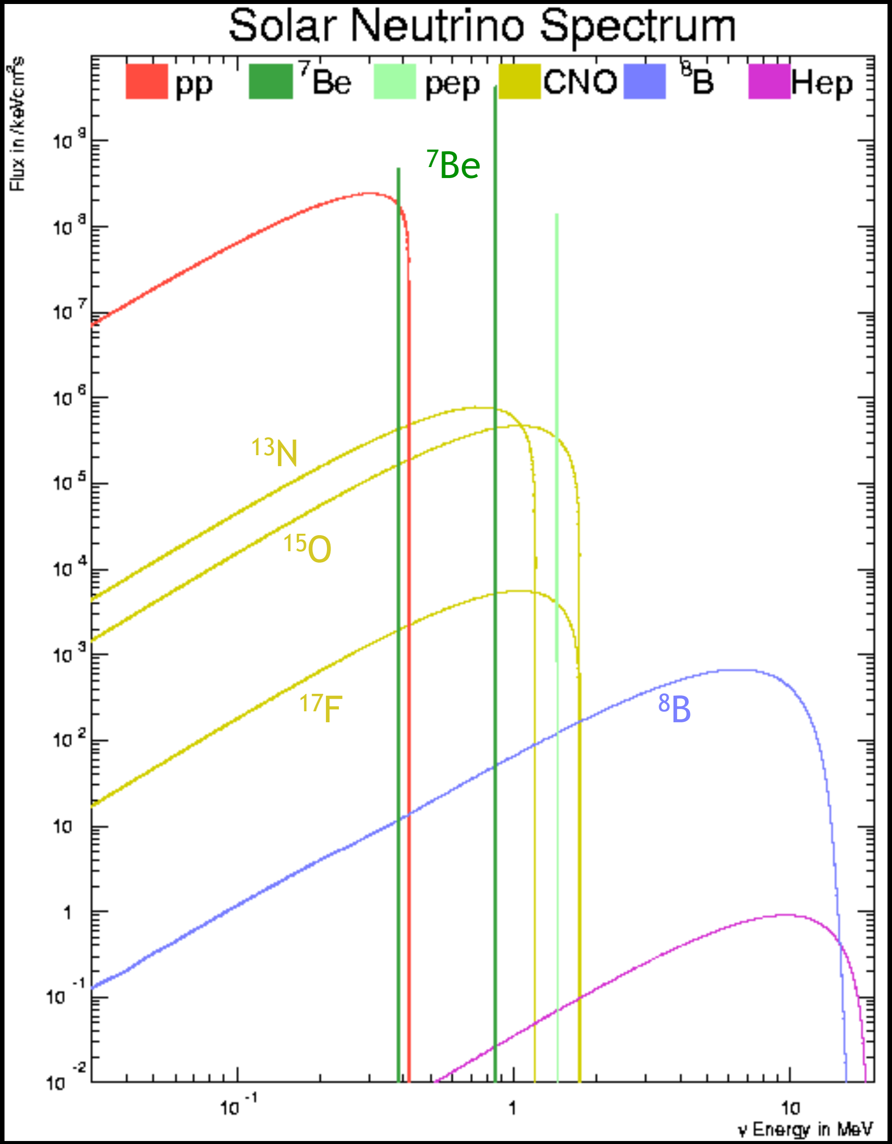
15.07%: ${}^7Be + e^- \rightarrow {}^7Li + \gamma + \nu_e$

${}^7Li + p \rightarrow {}^4He + {}^4He$

0.02%: ${}^7Be + p \rightarrow {}^8B + \gamma$

${}^8B \rightarrow {}^8Be^* + e^+ + \nu_e$

${}^8Be^* \rightarrow {}^4He + {}^4He$


Solar Neutrino Spectrum
pp
7Be
pep
CNO
8B
Hep
Flux in /keV/cm²/s
7Be
13N
15O
17F
8B
ν Energy in MeV
10^-1
1
10
10^9
10^8
10^7
10^6
10^5
10^4
10^3
10^2
10
1
10^-1
10^-2

Science Proposal

1. Solar neutrino sources and solar metallicity (Standard Solar Model)
   - What are the data needs for next generation solar neutrino experiments?
   - What is the absolute flux of neutrinos from the sun?
   - What is the solar core temperature?
   - What is the abundance of non-hydrogen nuclei?

2. Carbon-based stellar nucleosynthesis
   - What is the composition of stellar material after proton and helium burning (depending on the stellar mass)?
   - What is the progenitor material for supernova explosive nucleosynthesis?
   - What is the time scale for later stellar burning (carbon and oxygen phases) -- as a function of stellar mass?

3. Neutron sources for heavy element production (beyond Fe)
   - How large is the neutron production in stellar burning?
   - How significant is the slow neutron capture process for nucleosynthesis?

Science Need

DIANA

The NSAC long range plan :

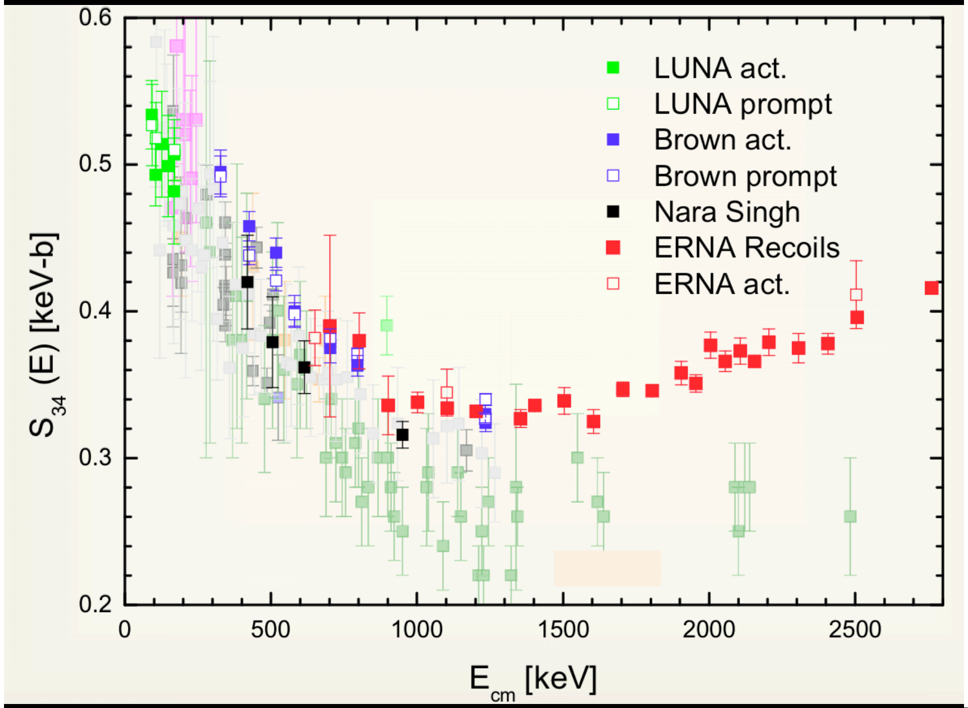
What are the nuclear reactions that drive stars and stellar explosions?

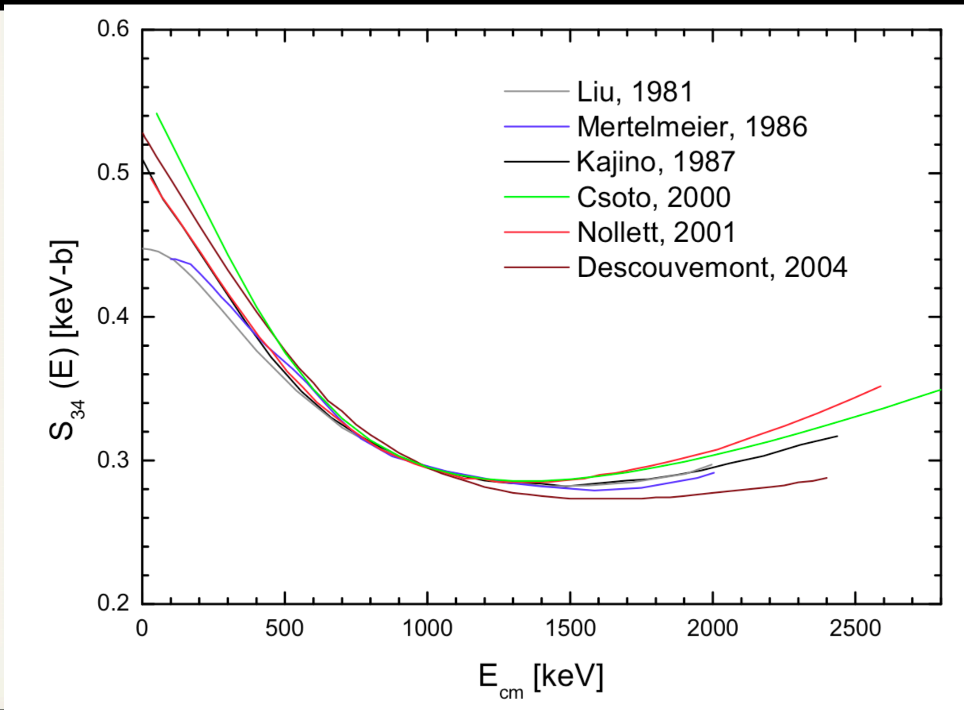
"… The extremely small cross sections of the stellar reaction rates result in the long liftimes of stars, but represent the main challenge to a direct experimental study. … Stellar models still suffer from large uncertainties in key nuclear reactions such as 12C(a,g) that then also affect the modelling of core collapes and Type 1a supernovae. … The largest handicap is the small cross section coupled with large natural background, which prohibits the detection of the characteristic reaction signals. The use of underground-based low-energy accelerator facilities [such as LUNA] reduces background by orders of magnitude. DUSEL will provide an opportunity for the development of such a facility in the United States."

The Frontiers Nuclear Science: A Long Range Plan **(December 2007)**

Somebody should measure S_{34}

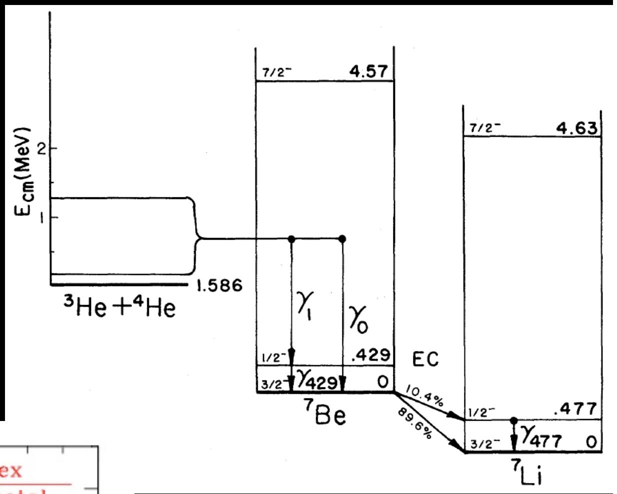
- Data on SSM inputs (including S_{34}) recently reviewed at INT meeting
  - http://www.int.washington.edu/PROGRAMS/solar_fusion.html
- Recent proposal for a phenomenological treatment of $S_{34}(E)$
- R.H. Cyburt, B. Davids, "Evaluation of modern $^3He(\alpha,\gamma)^7Be$ data," PRC 78, 064614 (2008)





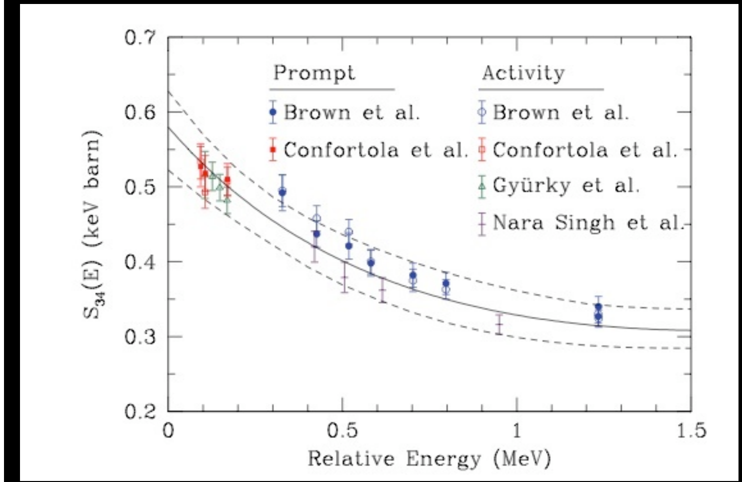
Somebody should measure S_{34}

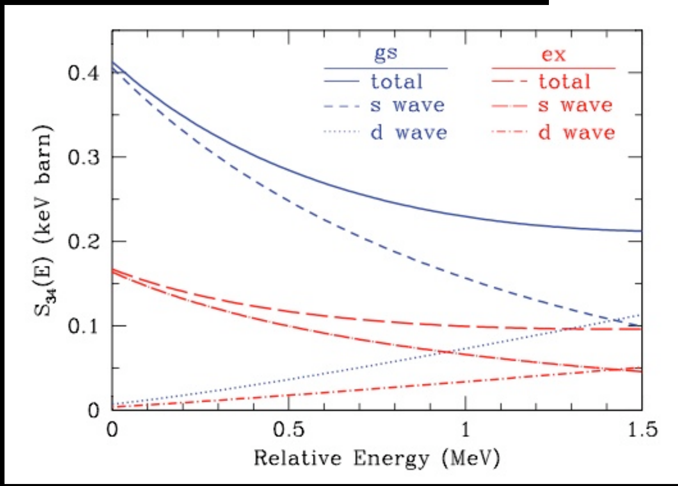
Recent proposal for a "nearly model independent" treatment of $S_{34}(E)$
R.H. Cyburt, B. Davids, "Evaluation of modern $^3He(\alpha,\gamma)^7Be$ data," PRC 78, 064614 (2008)



Partial wave parameters for
ground, first excited state reactions -- 5 parameters

Need 6 data points over energy range "0" < E_{CM} < 1.5 MeV

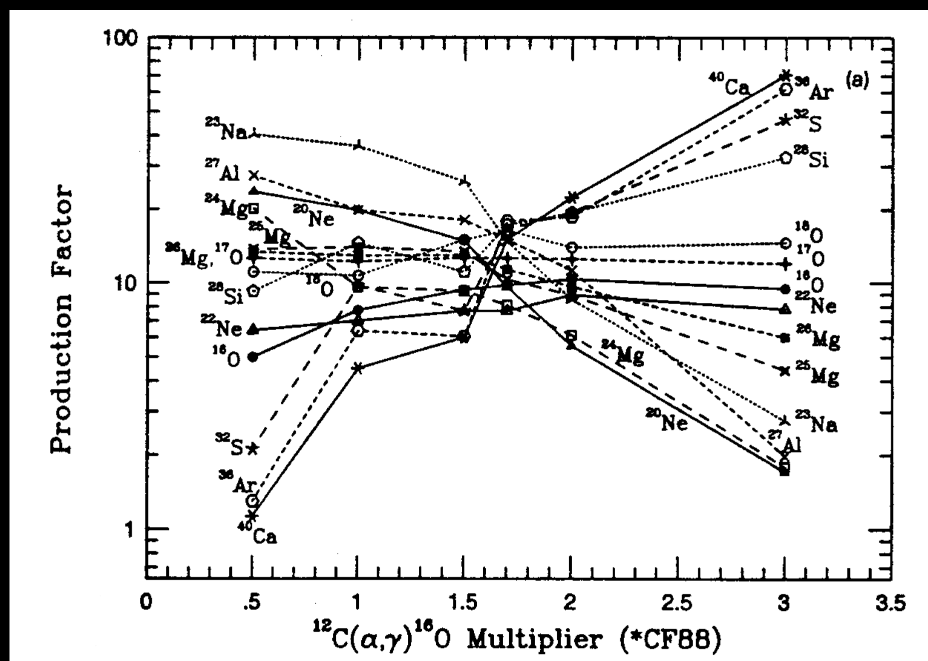




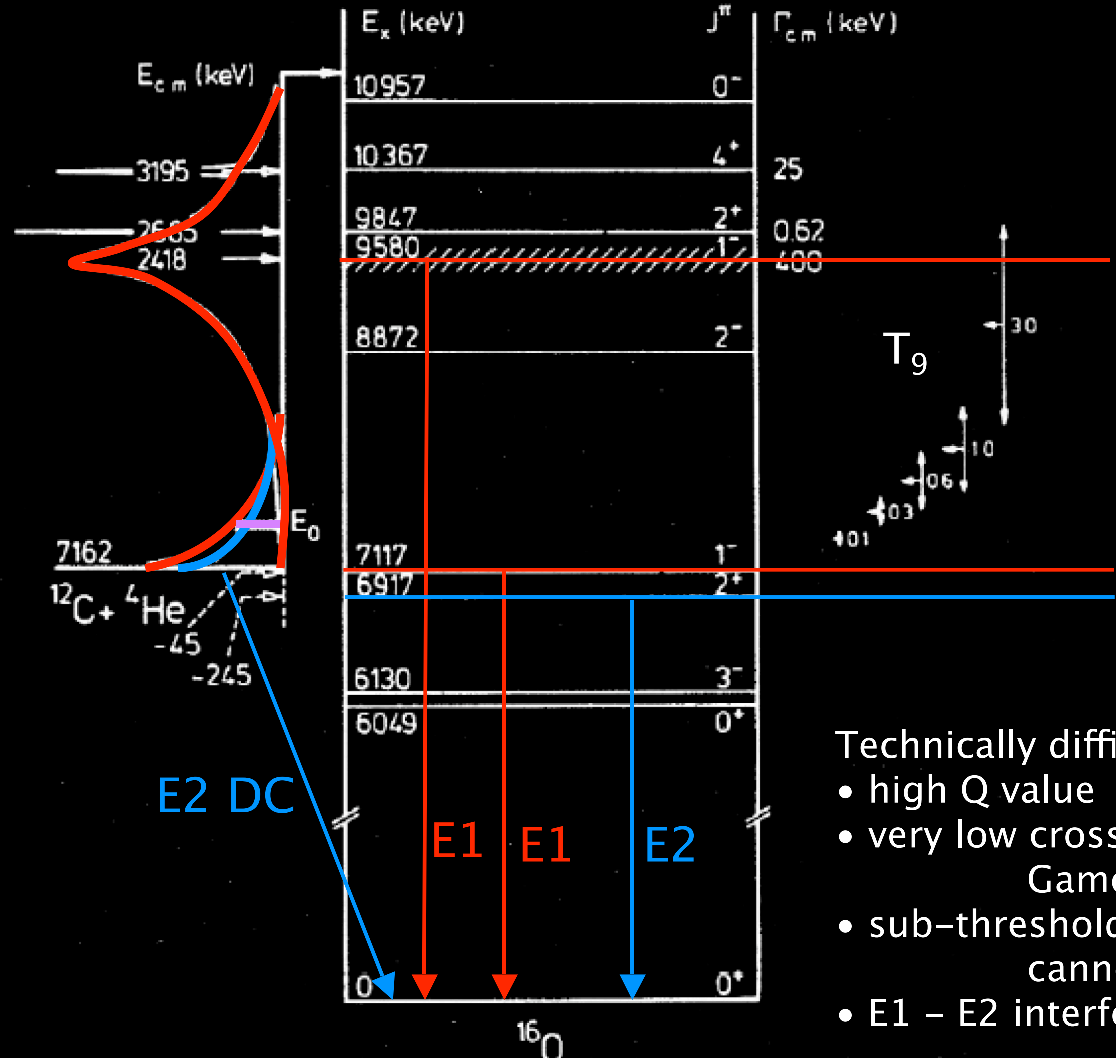
Carbon-based stellar nucleosynthesis

$^{12}C(\alpha,\gamma)^{16}O$ is the key reaction:

- Carbon/Oxygen ratio determines further stellar evolution
  C-burning or O-burning? Subsequent s-process…
- Iron core size (and other shell sizes)
  determines outcome of SN explosion
- Nucleosynthesis: shock front nucleosynthesis in SN type II



Intelligent Design and $^{12}C(\alpha,\gamma)^{16}O$

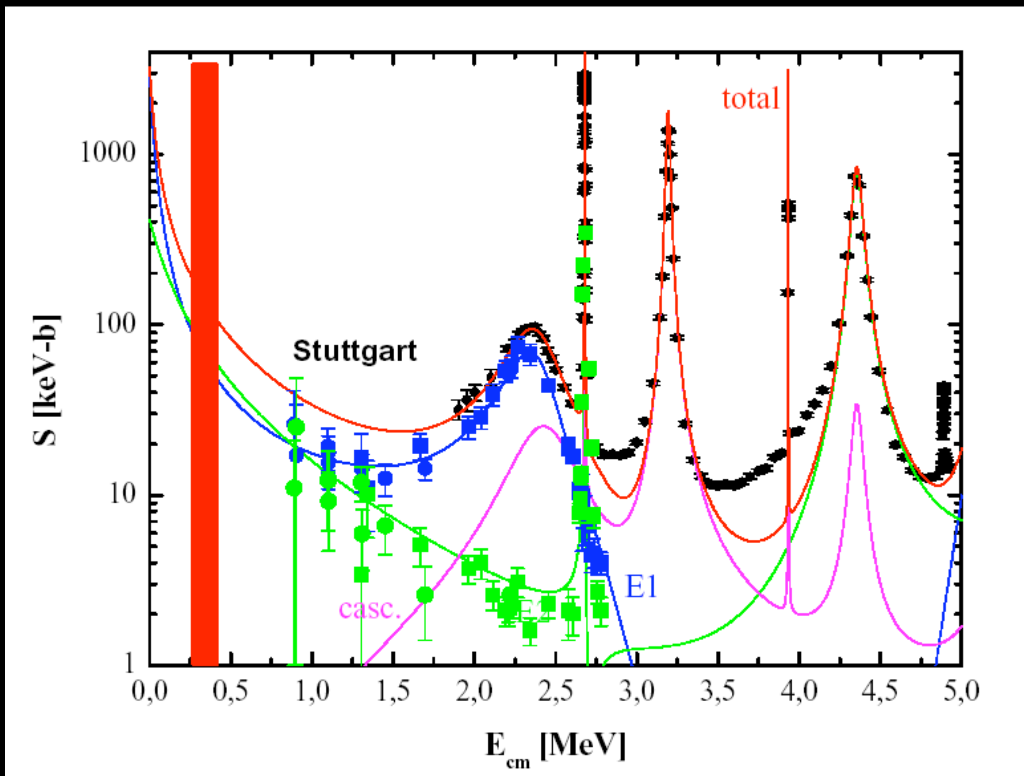


Sub-threshold resonances

Technically difficult:

- high Q value
- very low cross section:
  Gamow window measurement impossible
- sub-threshold resonances:
  cannot be measured at resonance energy
- E1 – E2 interference

$^{12}C(\alpha,\gamma)^{16}O$ existing data



Wide energy range with the same target is necessary to provide consistent data for a high quality extrapolation to low energies

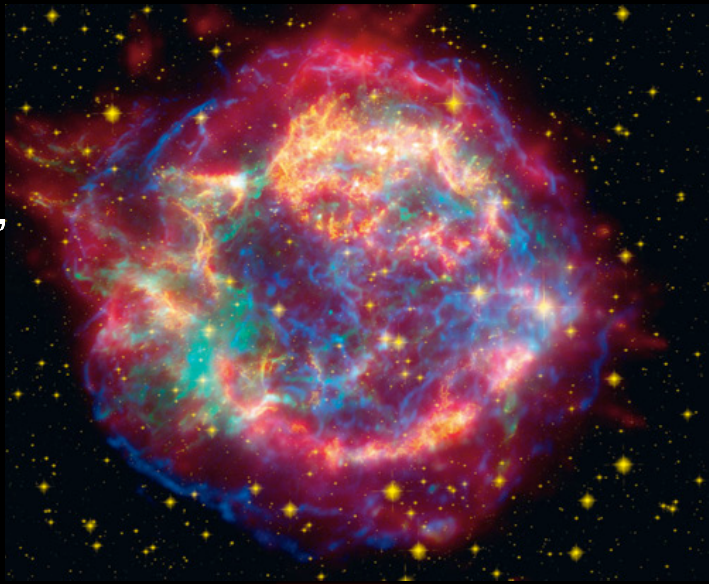
Gamow window $E_{CM} \sim 0.3$ MeV

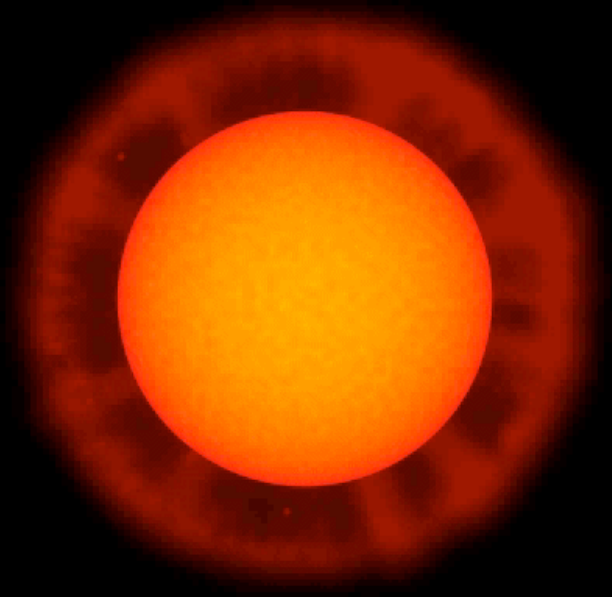
Above ground measurements stop at 0.9 MeV

DUSEL statistical goal: $E_{CM} \sim 0.7$ MeV

Neutron sources for heavy element production

DIANA





S-process nucleosynthesis

What is the neutron production rate in stars (slow), compared to explosive phases (rapid)?

What are the active neutron production rates in stable burning phases of red giants?

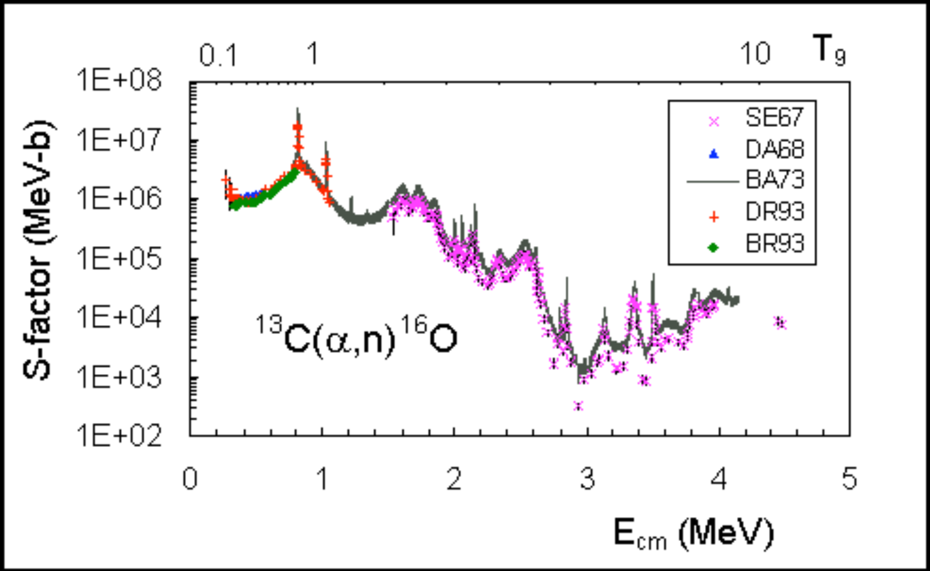
Two main reactions dominate s-process models:

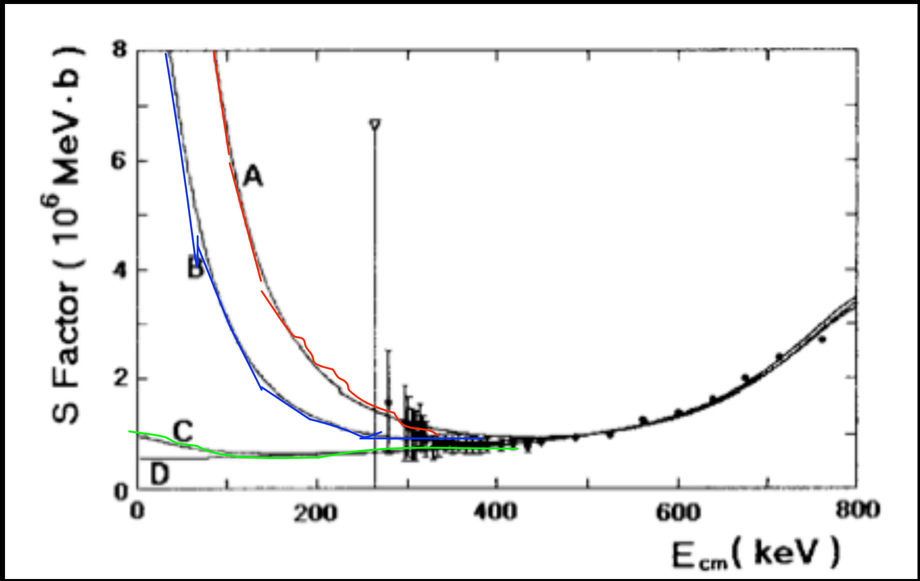
$^{13}C(\alpha,n)^{16}O$
$^{22}Ne(\alpha,n)^{25}Mg$

Neutron sources for heavy element production

$^{13}C(\alpha,n)^{16}O$ ~ responsible for 95% of neutron production in low-mass stars

main Red Giant phase neutron source at T_9 ~ 0.1





S. Kato et al. Nucl. Phys. A 718 189 (2003)

Goals for low-energy measurements

Seek sub-threshold part (E = -3 keV) suggested by R-matrix fit

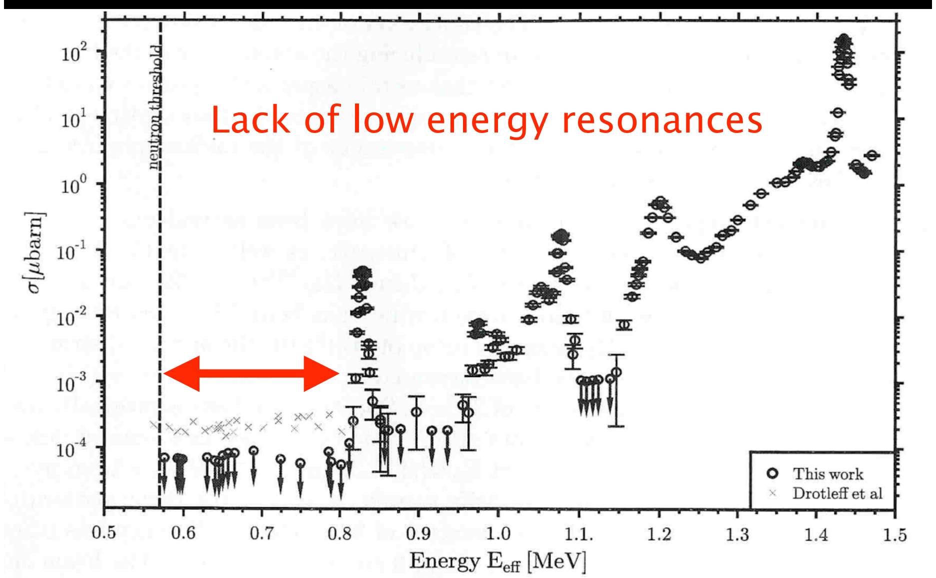
Higher energy measurements for resonant contributions

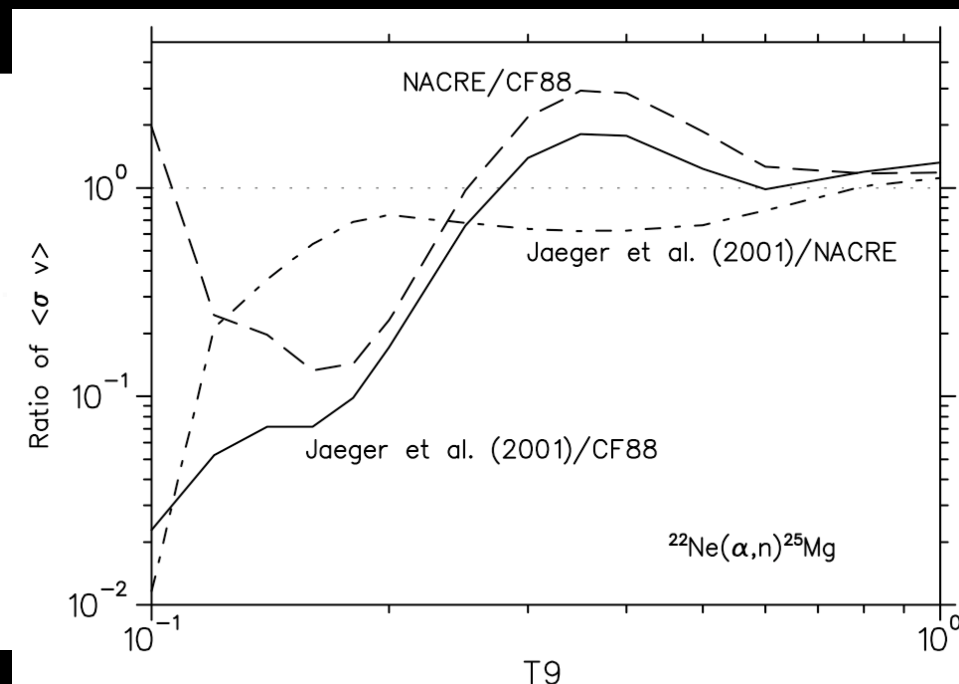
Low-energy, background suppressed, underground

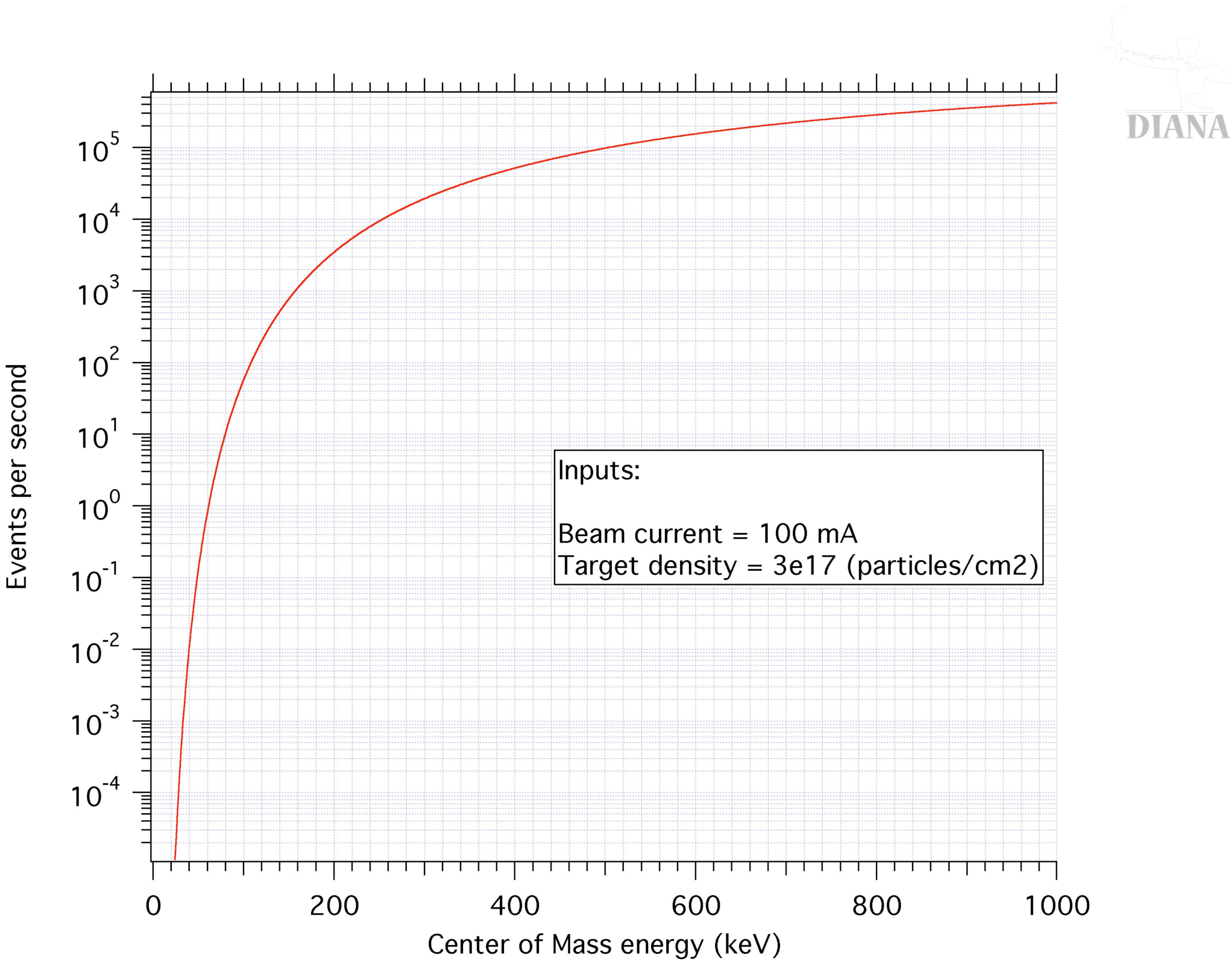
Neutron sources for heavy element production

$^{22}Ne(\alpha,n)^{25}Mg$

Similar problem with near-threshold resonances --
expected resonances don't show up in available data,
complicates extrapolation to low energy
Neutron production uncertain

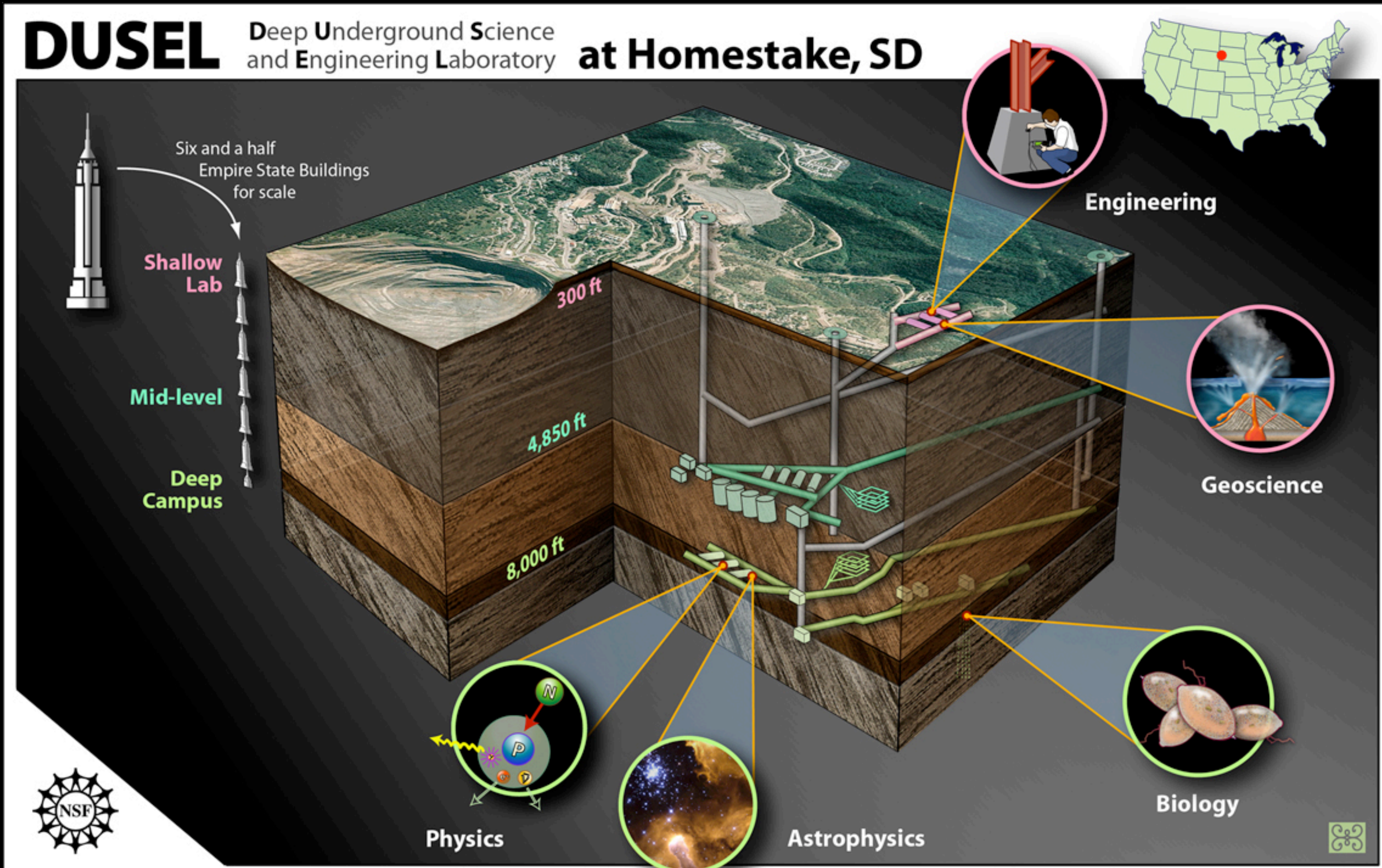




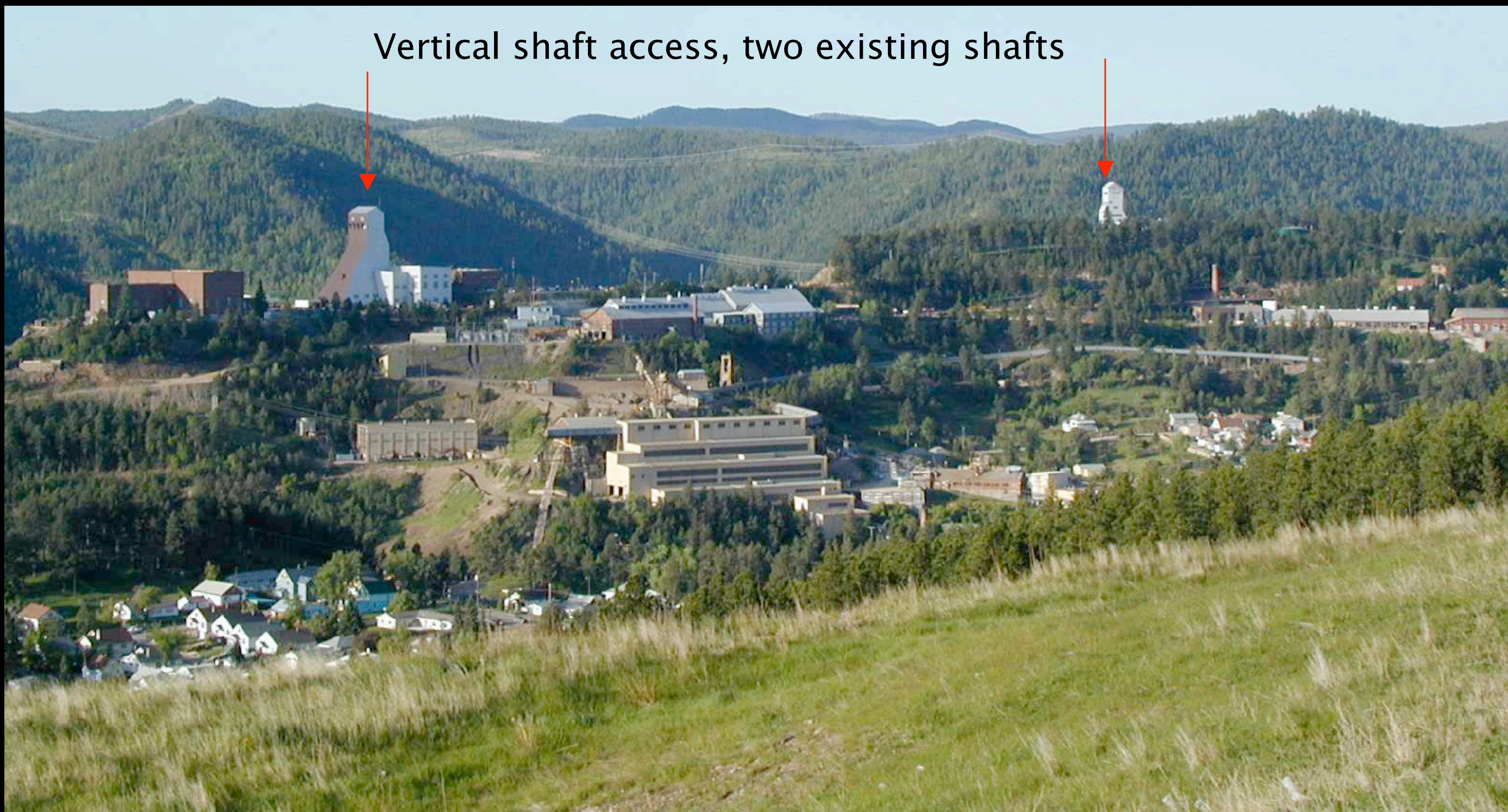


DIANA
Events per second
10^5
10^4
10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
200
400
600
800
1000
Center of Mass energy (keV)
Inputs:
Beam current = 100 mA
Target density = 3e17 (particles/cm2)

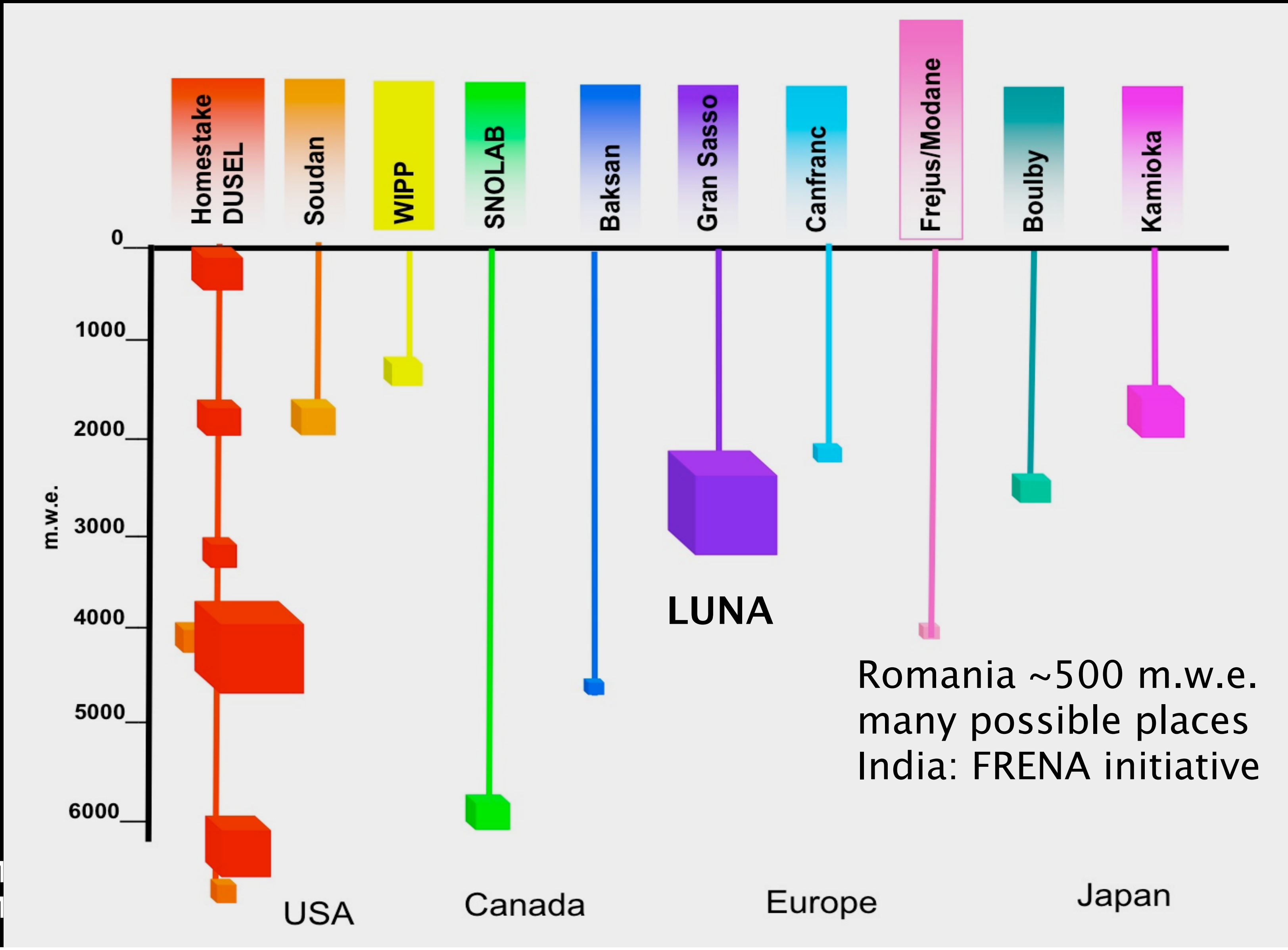
DUSEL Campus



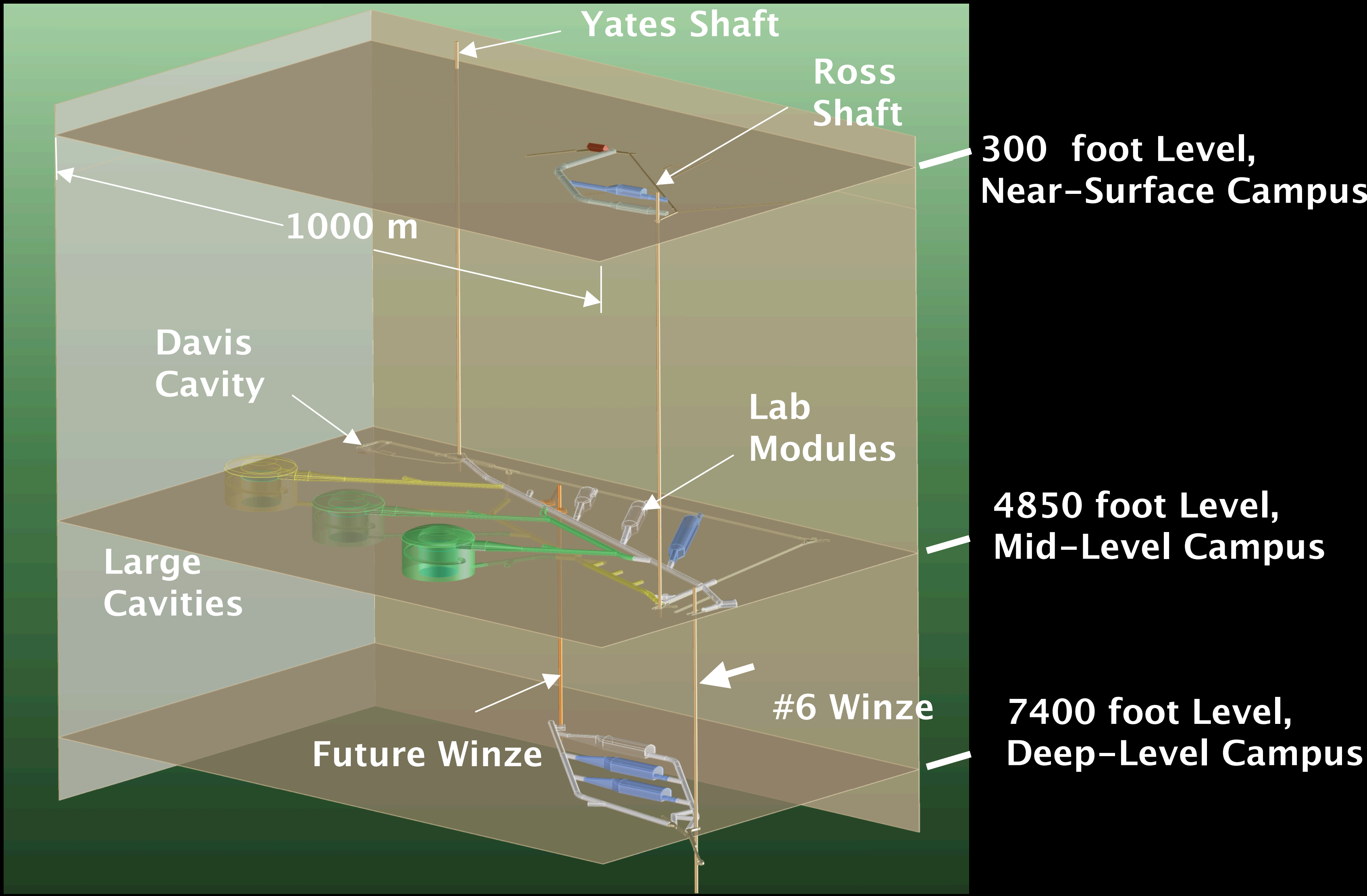
The DUSEL Homestake Site

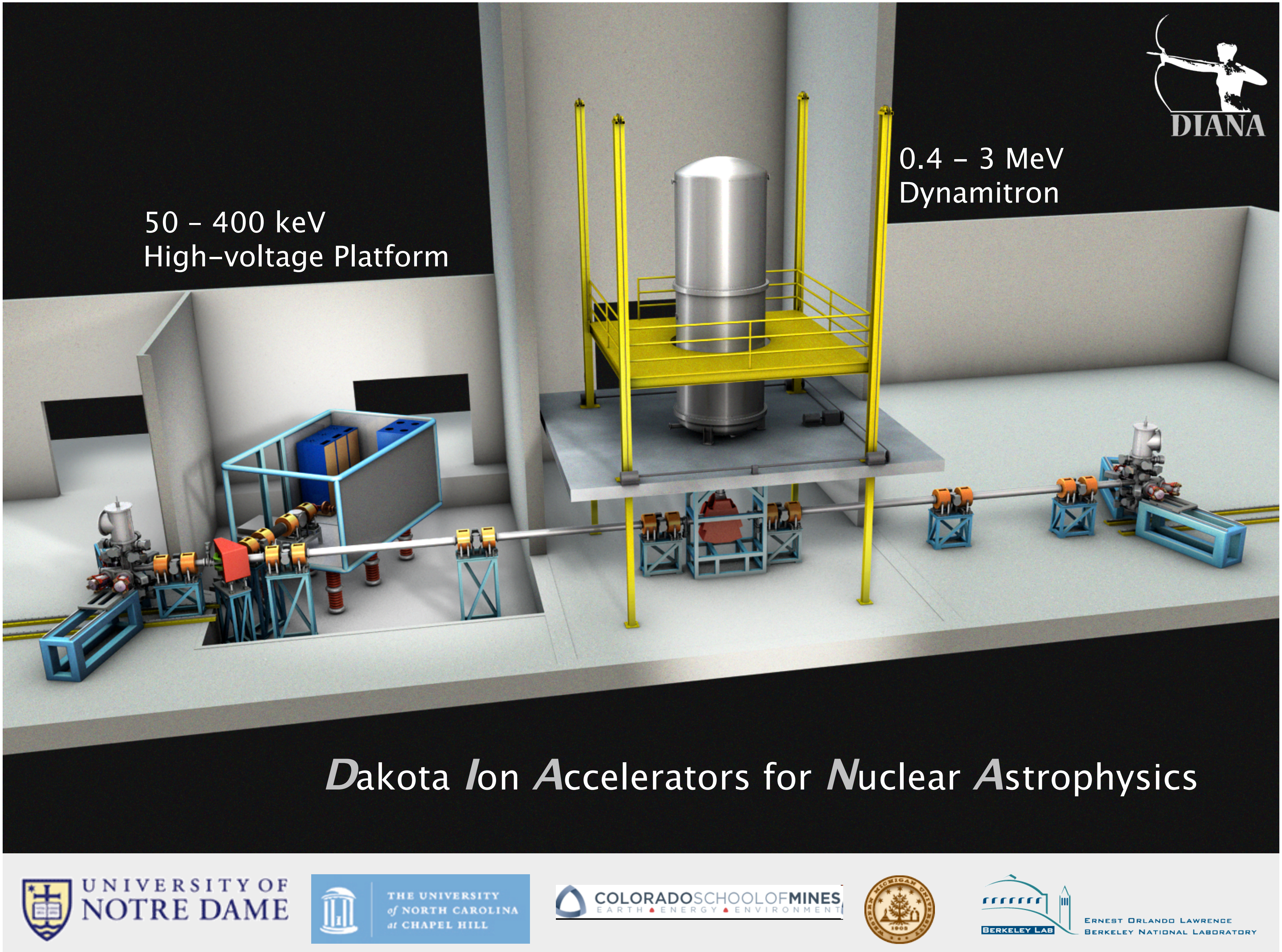


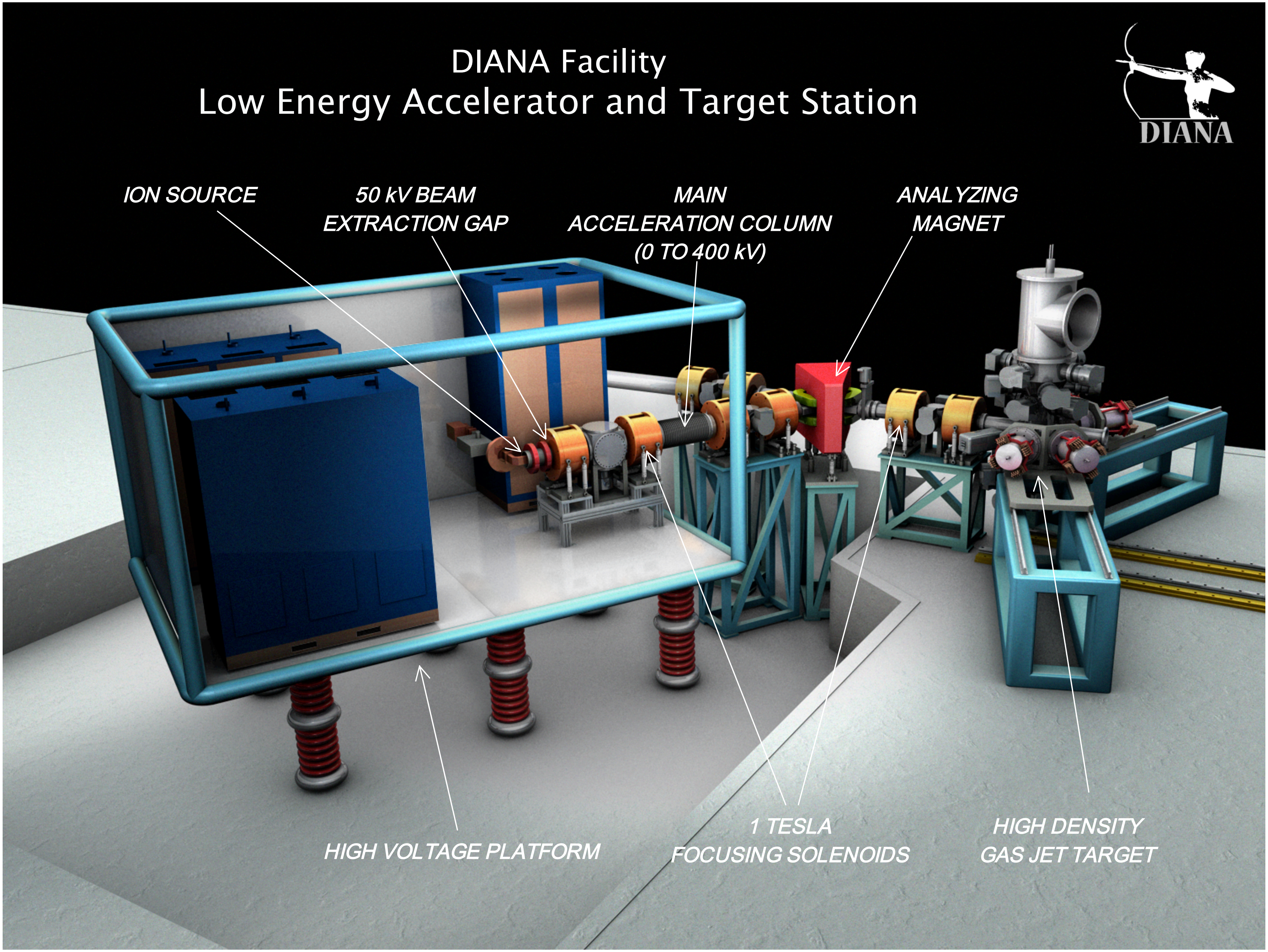
Underground labs with accelerators (proposed or running)

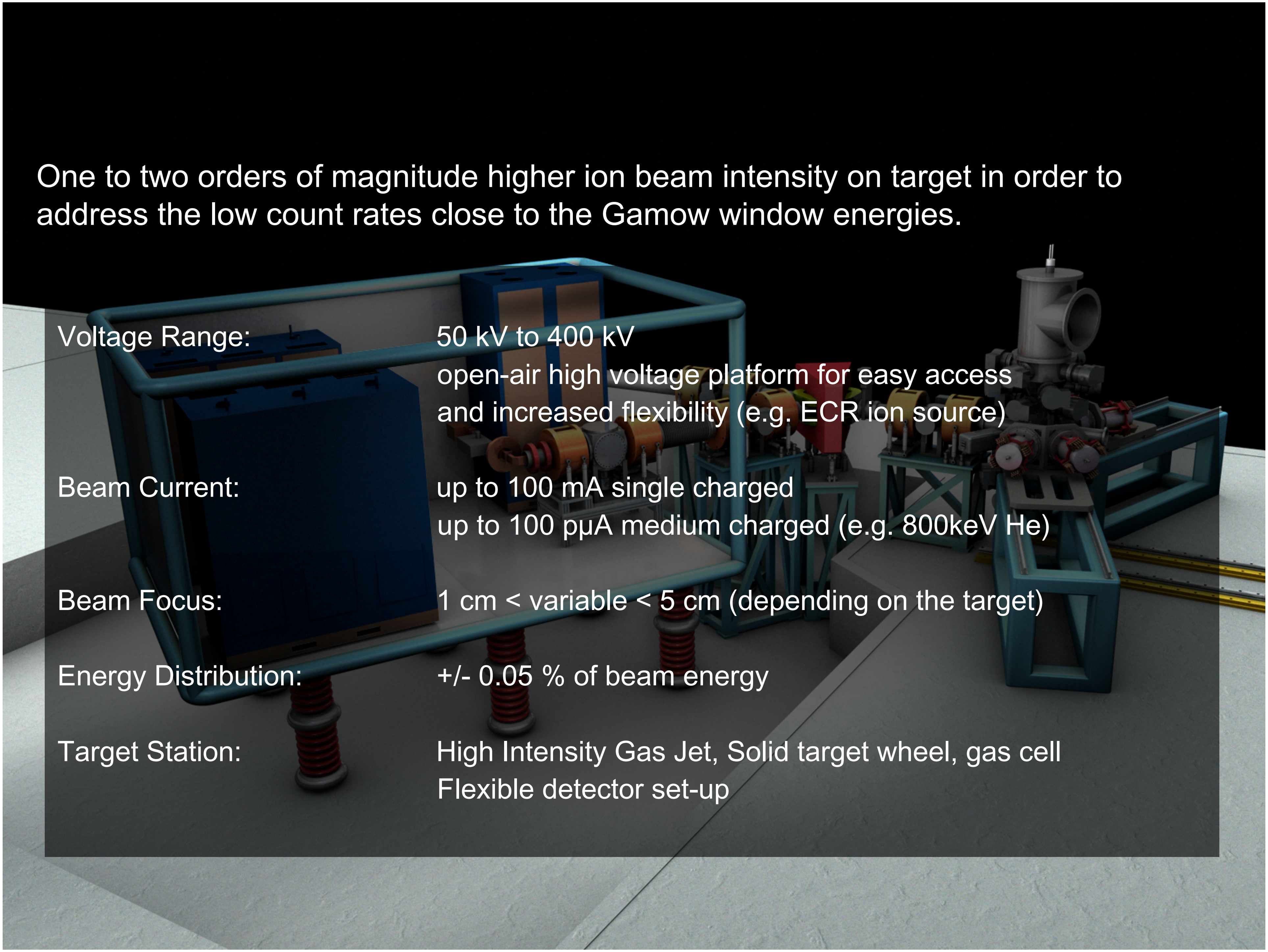


The DUSEL Homestake Site

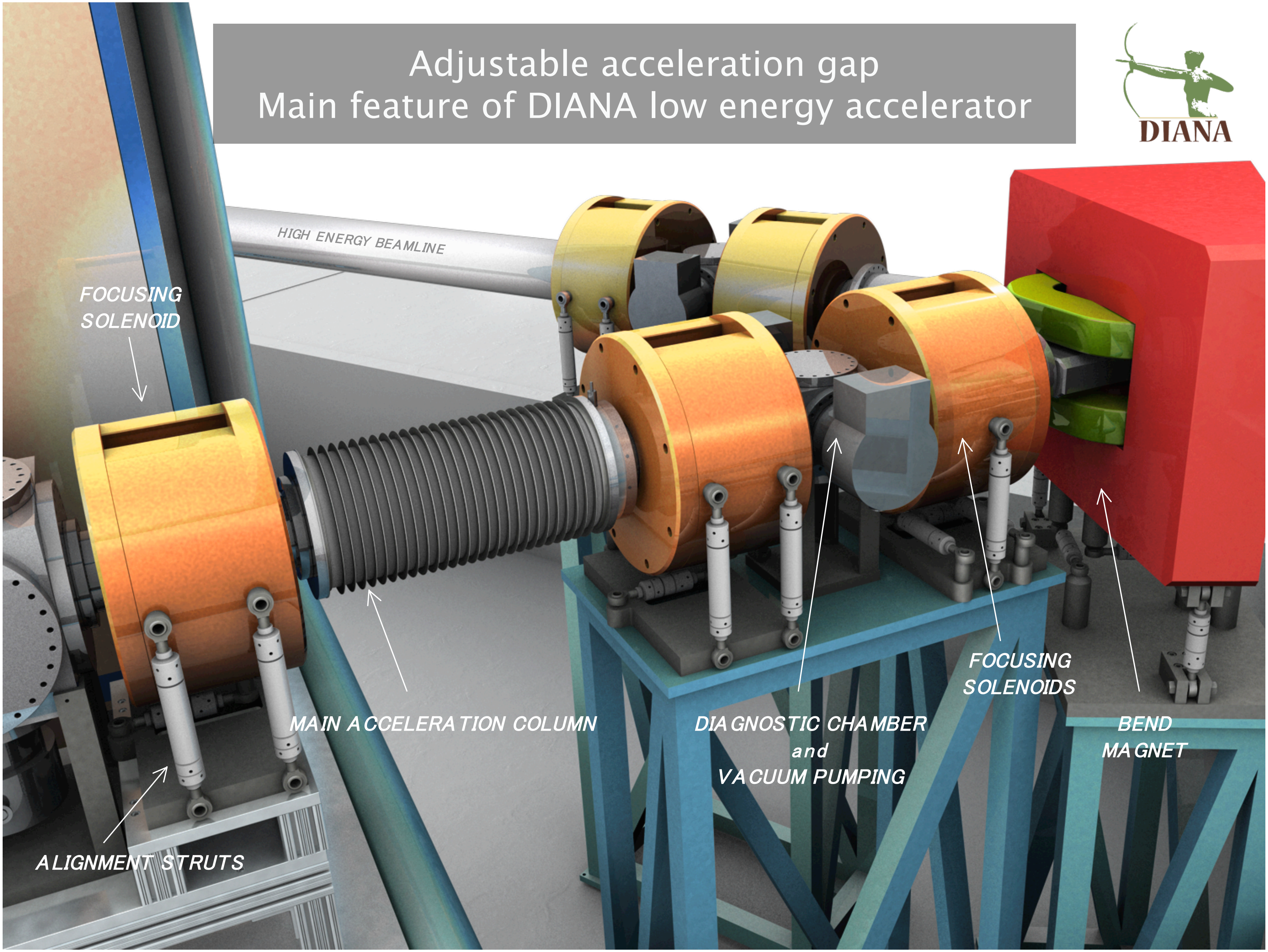



DIANA
0.4 – 3 MeV
Dynamitron
50 – 400 keV
High-voltage Platform
Dakota Ion Accelerators for Nuclear Astrophysics
UNIVERSITY OF NOTRE DAME
THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL
COLORADOSCHOOLOFMINES
EARTH • ENERGY • ENVIRONMENT
BERKELEY LAB
Ernest Orlando Lawrence
Berkeley National Laboratory

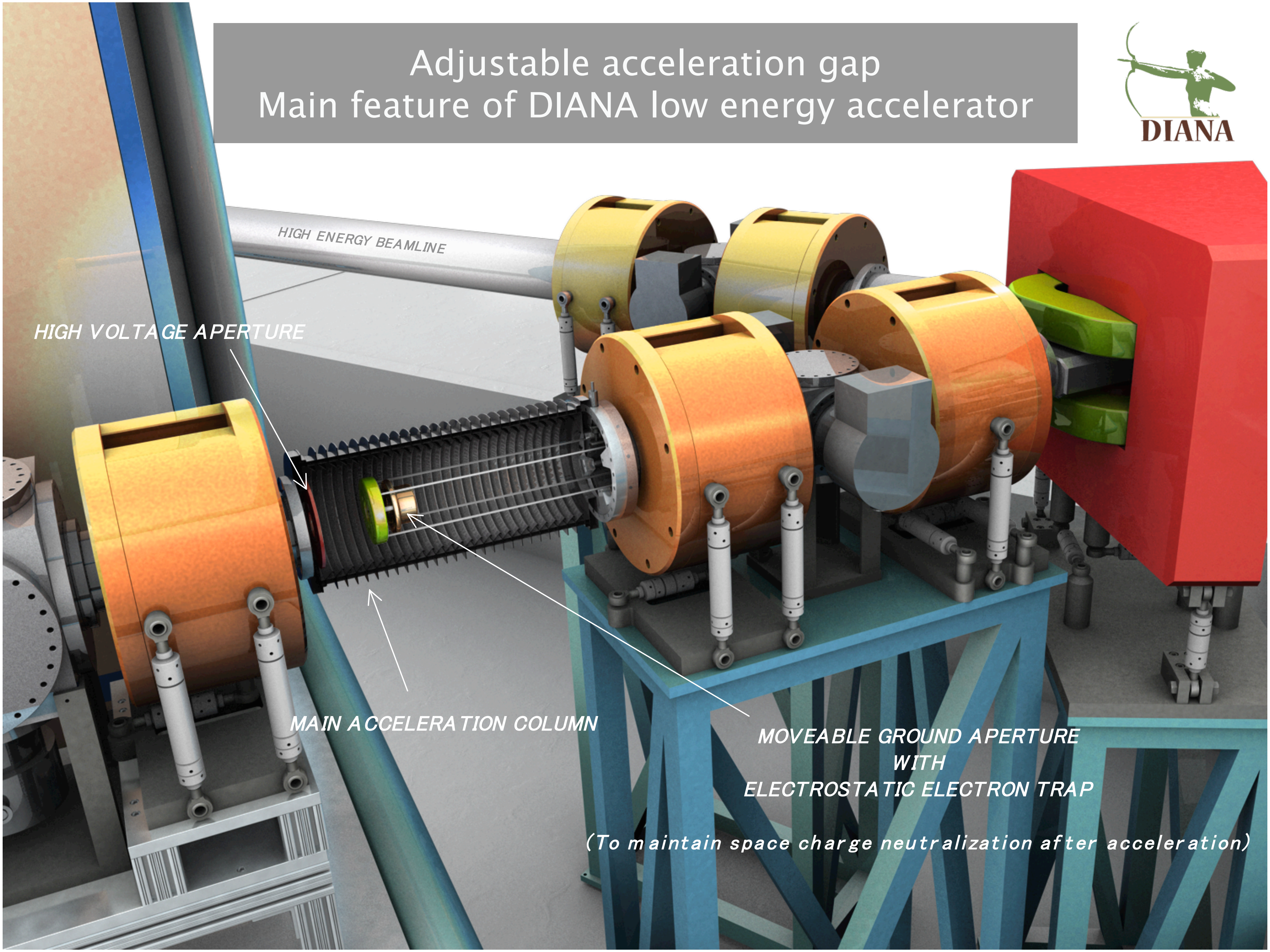

DIANA Facility
Low Energy Accelerator and Target Station
DIANA
ION SOURCE
50 kV BEAM
EXTRACTION GAP
MAIN
ACCELERATION COLUMN
(0 TO 400 kV)
ANALYZING
MAGNET
HIGH VOLTAGE PLATFORM
1 TESLA
FOCUSING SOLENOIDS
HIGH DENSITY
GAS JET TARGET


One to two orders of magnitude higher ion beam intensity on target in order to address the low count rates close to the Gamow window energies.
Voltage Range:
50 kV to 400 kV
open-air high voltage platform for easy access
and increased flexibility (e.g. ECR ion source)
Beam Current:
up to 100 mA single charged
up to 100 pμA medium charged (e.g. 800keV He)
Beam Focus:
1 cm < variable < 5 cm (depending on the target)
Energy Distribution:
+/- 0.05 % of beam energy
Target Station:
High Intensity Gas Jet, Solid target wheel, gas cell
Flexible detector set-up

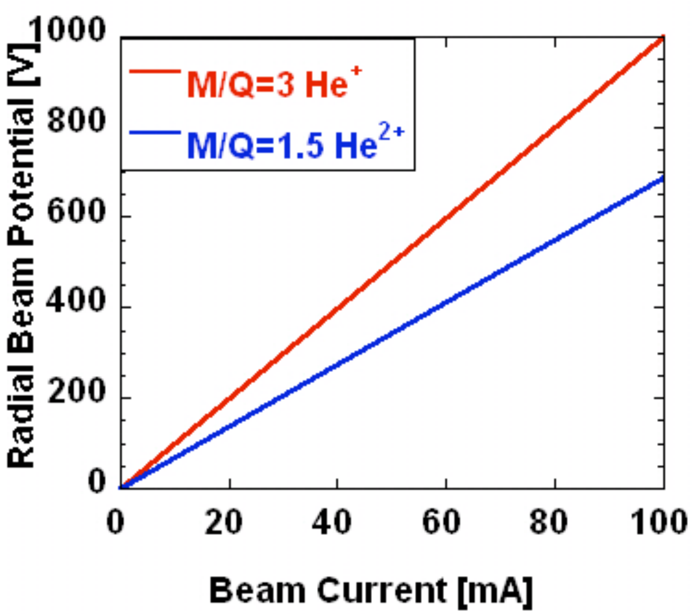
Adjustable acceleration gap
Main feature of DIANA low energy accelerator

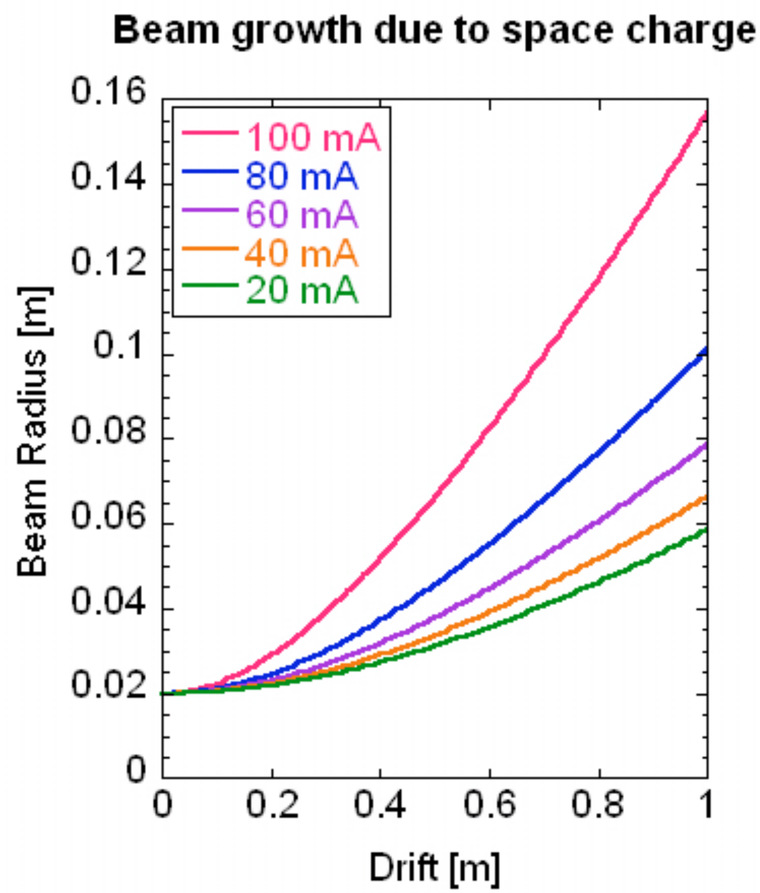


Adjustable acceleration gap
Main feature of DIANA low energy accelerator

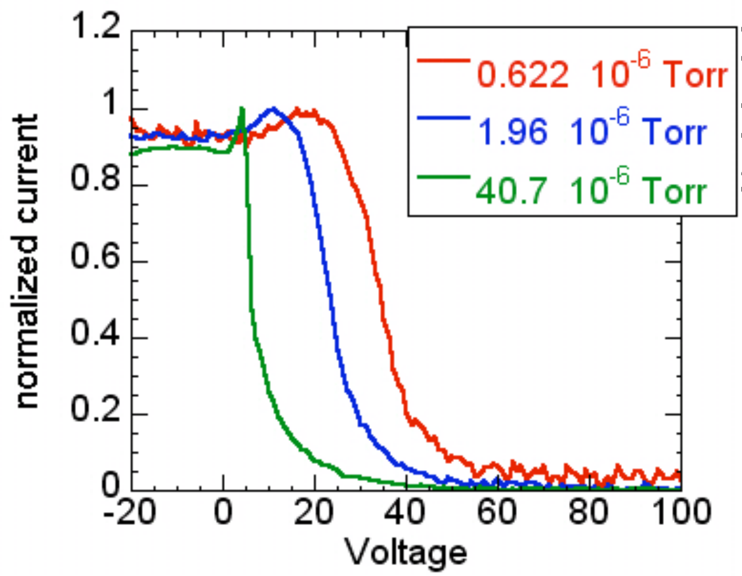


- Space charge at low acceleration voltage
  - Without some degree of neutralization a 100mA beam can't be transported at 50kV
  - Space charge can introduce an unacceptable energy spread





- Space Charge Neutralization
  - When the beam passes through residual gas, it gets partially ionized, positive ions are expelled by the beam potential, electrons are trapped in the beam potential and neutralize it (quasi neutralized plasma)
  - Degree of neutralization is depended
    - on the time structure of the beam
    - ...beam line
    - ...ctric fields – beam transport is ...using elements
  - ...ANA beam line assumes



Measurement of the beam potential due to space charge in the VENUS beam line

The beam potential decreases with increasing pressure

Current R&D topics

- Full costed design of accelerators, beamlines, magnets, vacuum systems
- Beam neutralization concept through mass analyzing magnets
- Interface of gas jet vacuum system with ion optic design
- Detector packages
  - High efficiency, large solid angle
  - High resolution, angle resolved HPGe
  - Neutron detection
- Background characterization and modelling
  - Incoming/outgoing Neutron shielding
- Education and outreach

Current status of DIANA@DUSEL

Submitted S4 proposal to NSF, awaiting funding decision -- end of summer, 2009.

Based on outcome of S4 work, S5 proposal would be submitted 2010

Begin construction ~2013